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CLIMATE CHANGE IMPACTS UNCERTAINTY FOR WATER RESOURCES IN THE SAN JOAQUIN RIVER BASIN, CALIFORNIA[1]

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ABSTRACT: A climate change impacts assessment for water resources in the San Joaquin River region of California is presented. Regional climate projections are based on a 1 percent per year CO_2 increase relative to late 20th Century CO_2 conditions. Two global projections of this CO_2 increase scenario are considered (HadCM2 and PCM) during two future periods (2010 to 2039 and 2050 to 2079). HadCM2 projects faster warming than PCM. HadCM2 and PCM project wetter and drier conditions, respectively, relative to present climate. In the HadCM2 case, there would be increased reservoir inflows, increased storage limited by existing capacity, and increased releases for deliveries and river flows. In the PCM case, there would be decreased reservoir inflows, decreased storage and releases, and decreased deliveries. Impacts under either projection case cannot be regarded as more likely than the other. Most of the impacts uncertainty is attributable to the divergence in the precipitation projections. The range of assessed impacts is too broad to guide selection of mitigation projects. Regional planning agencies can respond by developing contingency strategies for these cases and applying the methodology herein to evaluate a broader set of CO_2 scenarios, land use projections, and operational assumptions. Improved agency access to climate projection information is necessary to support this effort.
(KEY TERMS: climate change; snowpack; California; reservoir operations.)

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INTRODUCTION

Recent reports published by the Intergovernmental Panel on Climate Change (IPCC, 2001) and the U.S. Global Climate Change Research Program (USGCRP, 2001, unpublished report) suggest several expected impacts of global warming that bear consequences for U.S. water resources management: more extreme daily temperatures, more intense precipitation events, increased summer continental drying, increased risk of drought, etc. However, it is well recognized that regional climate changes are expected to vary significantly as global climate change evolves (USEPA, 1997; USGCRP, 2001, unpublished report; IPCC, 2001). Consequently, the development of region specific assessments of climate change impacts for the sake of regional water resources planning has emerged as a major area of active research.

This paper presents an assessment of the potential impacts on water resources in the San Joaquin River region of California. This region occupies the middle portion of California's Central Valley watershed (Figure 1). The northern portion of this watershed includes the Sacramento River and Delta regions. The southern portion includes the San Joaquin River region. Both the Sacramento and San Joaquin River regions produce runoff that flows through the Delta region and into the San Francisco Bay-Estuary.

A chief objective in conducting impacts assessments is to develop adequate guidelines to help affected parties direct their capital improvements efforts in a way that accommodates potential climate change. Given the fiscal requirements necessary for implementing capital improvements, it is important for resource managers and policy makers to understand the uncertainty of potential climate change impacts before investing in mitigation projects. Impacts uncertainty can be introduced at several stages of the

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assessment (e.g. selection of CO_2 increase scenario, climate modeling approach, operational assumptions). This assessment focuses on uncertainty introduced from different climate modeling approaches given a single CO_2 increase scenario, leading to different joint projections of precipitation and temperature and different associated impacts. Within this scope, the following assessment questions were considered.

- What are the potential impacts on reservoir inflows?
- What are the potential impacts on reservoir operations measured by monthly patterns of storage, releases, and water deliveries?
- What are the potential impacts on reservoir operations required for meeting water quality management objectives in the Delta region?

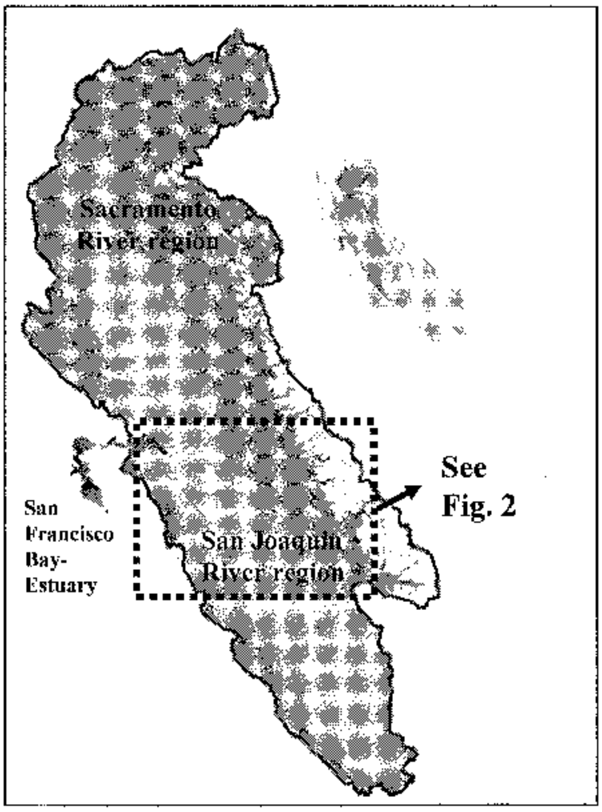

Figure 1. The Central Valley Watershed in California. Figure adapted from Knowles and Cayan (2002) and from the map on Knowles (2003).

This assessment contributes to the collection of studies that characterize potential climate change impacts on Central Valley water resources (e.g., Gleick, 1987; Lettenmaier and Gan, 1990; USBR, 1991; Dracup and Pelmulder, 1993, unpublished report; USEPA, 1997; Miller *et al.,* 1999). Earlier studies were conditioned by a key assumption that regional precipitation conditions will not change in response to regional warming. In contrast, this assessment considers precipitation projections jointly with temperature projections under a common CO_2 increase scenario.

Simulating impacts under the assumption of no precipitation change (e.g., Gleick, 1987; Dracup and Pelmulder, 1993, unpublished report) leads to several notable findings: warmer mean temperatures throughout the year, earlier snowmelt from the Sierra Nevada, and warmer winter storms that potentially produce more winter rainfall/runoff rather than snow accumulation in the Sierra Nevada. There is also the possibility that positive changes in winter runoff might be accompanied by increases in flood event severity and warrant additional dedication of wet season storage space for flood control rather than for supply conservation. Less winter supply development through storage or snowpack accumulation would lead to more frequent water shortages during the high water demand periods of summer and autumn. This could exacerbate current ground water overdraft conditions in the Central Valley (Quinn *et al.,* 2001). To summarize, there is general agreement in earlier studies on what potential climate change impacts might be on the Central Valley watershed if regional warming occurs *given no precipitation change*.

Recent studies have relaxed the assumption of no precipitation change and impacts assessments are instead driven by precipitation projections from global climate models downscaled over California (Miller *et al.,* 2003). These studies show great uncertainty in projected precipitation and hydrologic impacts within the Central Valley. Much of the uncertainty of global precipitation projection given CO_2 increase scenarios is due to model structure assumptions (IPCC, 2001). There is currently no guidance from the climate modeling community to suggest which of the global climate models included in the IPCC report (2001) has superior model structure for projecting California regional precipitation. Therefore, any precipitation projections produced for California using one of the IPCC referenced global climate models (2001) under a common CO_2 increase scenario would have to be regarded as being similarly or equally possible. Thus, if two or more of these equiprobable projections are used to drive an impacts assessment, then the sets of impacts referenced to each of the projections would form a range of impacts with uniformly weighted probability of occurrence. The results of this assessment are interpreted using this viewpoint, as indicated in the discussion section.

The next section of this paper highlights key hydrologic and water system features of the San Joaquin River region. A Methods Section discusses the assessment assumptions and methodologies, followed by a presentation of key results (Results), a discussion on the relevance of these findings from a planning perspective (Discussion), and a summary of major conclusions (Conclusions).

BACKGROUND ON WATER RESOURCES OF THE SAN JOAQUIN RIVER BASIN

The water resource systems of the San Joaquin River region are among the most constrained in the nation, as they try to meet water supply, water quality, flood control, ecosystem, and recreation objectives. Nearly one quarter of the inflow into the Delta region originates from the San Joaquin River and its tributaries (Figure 2). This inflow, combined with the large flows from the Sacramento River region, becomes a drinking water supply source for approximately 20 million people in central and southern California (Brickson, 1997). Runoff from the San Joaquin River region affects hydrodynamic conditions in the Delta, particularly during wet years. This bears influence on the Delta's ability to support migratory bird and anadromous fish species (Brickson, 1998). Economically, the region contains one of the world's most fertile agricultural valleys, where agricultural production is valued at approximately $4 billion annually (Brickson, 1998).

The primary east side source of water supply to the San Joaquin River region is local surface water runoff from the Sierra Nevada. This supply arrives mainly as spring and summer snowmelt into surface water reservoirs on the four major tributaries of the main stem San Joaquin River: New Melones Reservoir on the Stanislaus River, Don Pedro Reservoir on the Tuolumne River, Lake McClure on the Merced River, and Millerton Lake on the upper San Joaquin River (Figure 2). New Melones Reservoir and Millerton Lake are part of the Central Valley Project (CVP) operated by the U.S. Bureau of Reclamation (USBR).

Regional water supplies are augmented on the west side through CVP operations, where supplies are imported from the Sacramento River region via the Delta. These supplies first flow into the Delta from the north and are then pumped out of the Delta on its south side into "export" canals that convey this water to South-of-Delta users. These "export" supplies can be delivered directly to users or temporarily stored in the San Luis off-stream reservoir (Figure 2) for delivery at a later date.

METHODS

Climate Change Scenario and Projections

Impacts uncertainty is characterized in this assessment by considering two "bracketing" climate projections of the same CO_2 increase scenario. The scenario is a 1 percent per year increase in mean global CO_2 relative to present day conditions. This scenario was

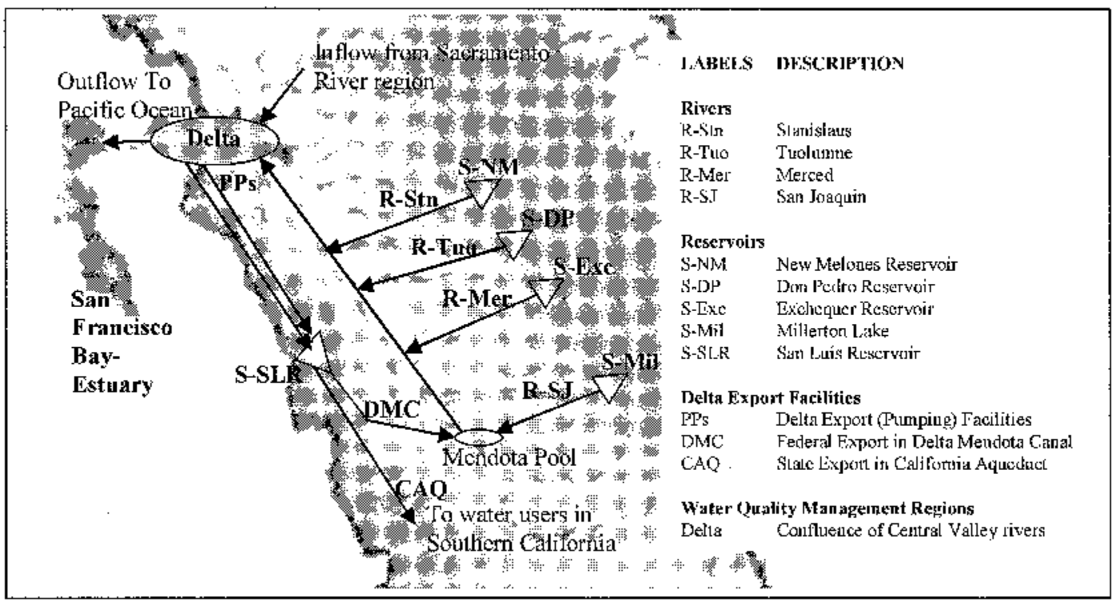

Figure 2. Schematic of Hydrologic and Water System Features in the San Joaquin River Region (shown in the Central Valley context from Figure 1).

used for the Coupled Model Intercomparison Phase 2 experiment, where output from different global climate models was compared given the circumstance of simulating the same CO_2 increase scenario (IPCC, 2001). It is acknowledged that the CO_2 content of the atmosphere has not increased at a rate of 1 percent per year. However, the 1 percent rate of increase is assumed to account for "equivalent" CO_2 increase that represents increases in other greenhouse gases such as methane and NO_x (IPCC, 2001). The IPCC report notes that a 1 percent per year increase in "equivalent" CO_2 is within the range of increases represented in the IPCC Special Report on Emissions Scenarios (IPCC, 2001).

The global climate effects of our assumed CO_2 increase scenario have been simulated by different climate models to produce numerous climate projections, two of which form the basis for California climate projection in this assessment (Miller *et al.,* 2003). The two projections are the "HadCM2 run 1" simulated using HadCM2, developed by the U.K. Hadley Center; and the "PCM run B06.06" simulated using PCM, developed by the U.S. National Center for Atmospheric Research. Both HadCM2 and PCM are coupled atmosphere ocean general circulation models. Both were used to develop projections that were considered along with others to assess potential global and regional climate impacts for the IPCC Third Assessment Report (IPCC, 2001).

California region warming rates are somewhat consistent between the two models. However, the HadCM2 projection suggests much wetter future conditions relative to present climate, whereas the PCM projection suggests drier future conditions (Miller *et al.,* 2003, and the next section). Both the HadCM2 and PCM projections were judged relative to other projections that could have been used for projecting California region climate change under the CO_2 increase scenario used here (i.e., those listed for the CMIP2 scenario in Table 9.1 of the IPCC report). The metric used to make this judgment is the model's "Transient Climate Response," or TCR, which equals the model's simulated change in mean global air temperature at the time of CO_2 doubling under the 1 percent per year increase scenario (IPCC, 2001). TCR values ranged from 1.1°C to 3.1°C for the 19 comparable model projections in the IPCC report. The TCR of the HadCM2 is 1.7°C and ranks ninth highest. The TCR of the PCM projection is 1.27°C and ranks second lowest. It was concluded that neither projection is an extreme outlier among available projection choices based on simulated temperature sensitivity to CO_2 increases. No metrics were provided in the IPCC report to allow analogous judgment based on simulated precipitation sensitivity.

Hydrologic Response Development

Miller *et al.* (2003) studied how global climate projections from HadCM2 and PCM translated into different hydrologic regimes in five tributaries to the Central Valley watershed: the upper Sacramento River gauged at the town of Delta (upstream of Lake Shasta), the Feather River gauged at Oroville Dam, the North Fork of the American River gauged at North Fork Dam, the Merced River gauged at Pohono Bridge, and the Kings River gauged at Pine Flat Dam. They considered hydrologic sensitivity to climate change using average monthly conditions during two future projection periods, 2010 to 2039 and 2050 to 2079, relative to average monthly conditions during the present climate. The future projection periods are labeled, respectively, by their mid-years: 2025 and 2065.

Streamflow for each basin and each projection period case (i.e., HadCM2025, HadCM2065, PCM2025, and PCM2065) was simulated using an application of the "National Weather Service-River Forecast System Sacramento Soil Moisture Accounting Model" (Burnash *et al.,* 1973) coupled to the Anderson Snow Model for computing snow accumulation and ablation (Anderson, 1973). The models were operated on a daily time step to simulate runoff in response to a forcing of mean area precipitation and temperature data archived by the National Weather Service (NWS) from 1963 to 1992. The models were validated during this same period using daily streamflow archived by the NWS. To simulate streamflow under each projection period case, mean area precipitation and temperature data had to be developed on a daily basis in relation to the HadCM2025, HadCM2065, PCM2025, and PCM2065 cases. The methodology for this data development step involved statistical downscaling of global climate model output over the California region to a spatial scale that was compatible with the basin areas. The Parameter Elevation Regressions on Independent Slopes Model developed by Daly *et al.* (1994) was used to complete the downscaling process. Further details of the data downscaling procedures and hydrologic response modeling are provided in Miller *et al.* (2003).

Hydrologic responses to each projection period case were computed by Miller *et al.* (2003) as ratios of monthly mean streamflow under climate change relative to monthly mean streamflow from 1963 to1992 (reproduced in Figure 3). Those ratios served as a basis for generating time series of reservoir inflow data under each projection period case for the reservoir operations model used in this assessment.

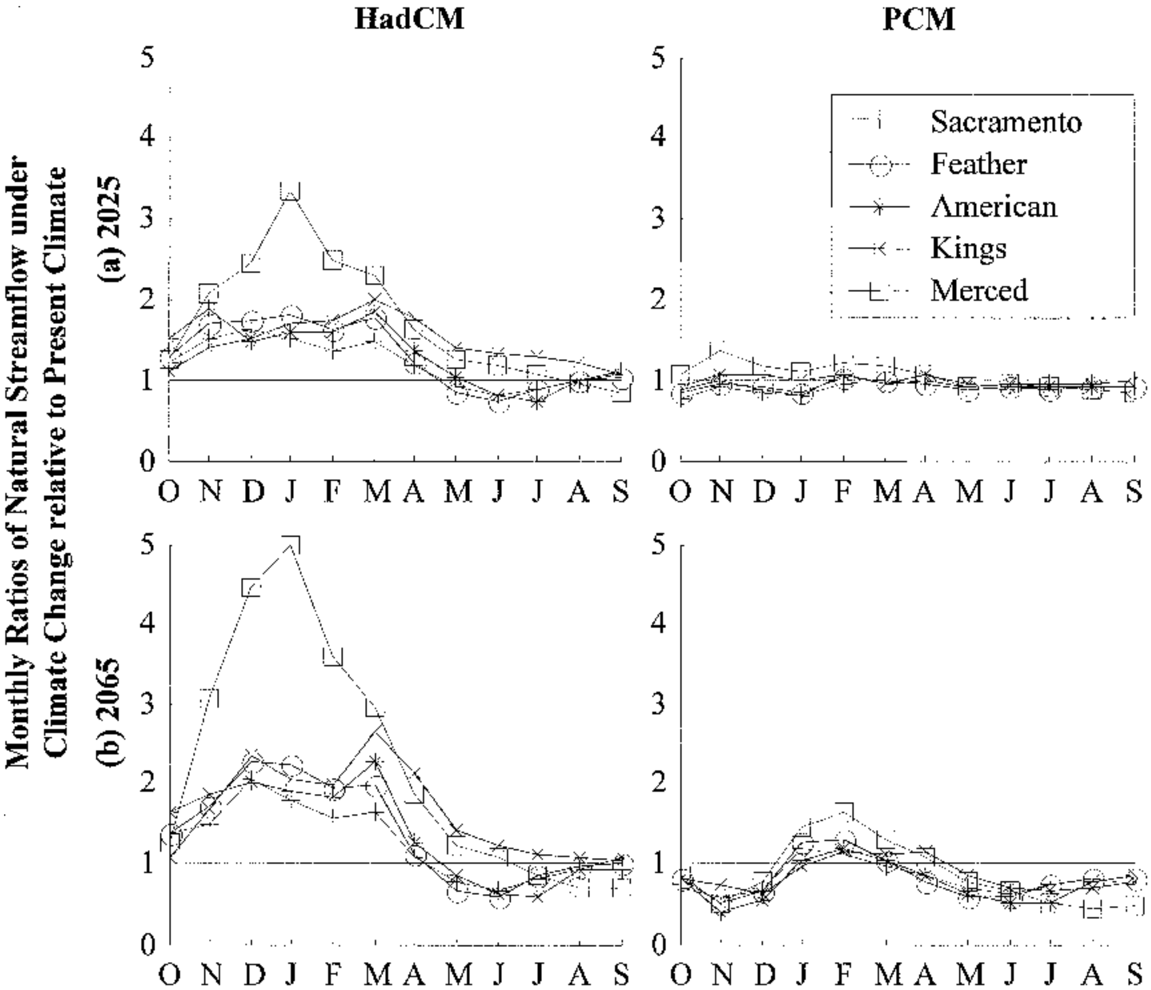

Figure 3. Hydrologic Responses to HadCM2 and PCM Climate Projections Shown as Ratios of Monthly Mean Natural Runoff in Each Projection Period Case: (a) 2025" representing projection years 2010 to 2039, and (b) "2065" representing projection years 2050 to 2079) relative to the present climate case (i.e., archived streamflow from 1963 to 1992) for five tributaries of the Central Valley watershed (Miller *et al.,* 2003).

Geographic Modeling Domain and Land Use Assumption

To assess climate change impacts on water resources management in the San Joaquin River region, it was necessary to simulate management activities in the combined Sacramento River, San Joaquin River, and Delta regions. This is because the San Joaquin River region receives west side water supplies from the Delta and Sacramento River regions (Figure 2). Also, the majority of the region's surface water supplies arrive via the federal Central Valley Project (CVP), which occupies the greater Central Valley and is operated in coordination with the California State Water Project (SWP). Coordinated operation of these two systems supports fisheries restoration and water quality management throughout the Central Valley and in the Delta. Additionally, there are independent water systems on major tributaries of the San Joaquin River that affect operation of the CVP and SWP systems (i.e., Don Pedro Reservoir on the Tuolumne River and Lake McClure on the Merced River). Therefore, it is necessary to simulate the interrelated local, state, and federal systems serving the San Joaquin River region, but occupying the greater Central Valley.

Simultaneous with selection of an operations model and geographic modeling domain is selection of a land use scenario for defining water demand conditions. In this assessment, land use was assumed to be constant and representative of Year 2001 levels. Future land use uncertainties compound the impacts uncertainties already attributable to the CO_2 increase scenario, climate modeling approach, and other operations assumptions. There is potential for synergistic response between land cover change and climate change as atmospheric CO_2 increases. For this assessment, synergistic responses involving Central Valley land cover and regional climate changes were not considered. This assumption is discussed as an assessment limitation in the Assessment Limitations Section.

Reservoir Operations Model and Water Allocation Priorities

Monthly operations for the CVP and SWP systems were simulated using the "CALSIM II Benchmark Study G-Model" with Year 2001 land use assumptions (Baseline) developed by the CVP and SWP management agencies (CDWR, 2001). The Baseline model represents the physical facilities for state, federal, and local systems of the greater Central Valley and codified rules governing the operations of these systems. Water is routed through the systems on a monthly basis using a linear programming / mixed integer programming solver. Model output includes monthly reservoir releases, river flows, reservoir stored water volumes, Delta export activities, and indicators of Delta water quality conditions.

The Baseline model is set up to perform monthly operations decisions for a 73-year simulation period that is referenced to 1922 through 1994 meteorological years experienced historically in the Central Valley. Weather data from these years were used to develop the hydrological assumptions in the Baseline model. Those assumptions include valley floor water demands based on Year 2001 land use, interactions between ground water and surface water in valley floor service areas, availability of ground water supplies, and headwater basin inflows into the 18 major surface water reservoirs that are included in the Baseline model.

The philosophy of how water is routed through the system is a key assumption in any reservoir operations model. This philosophy translates into allocation tradeoffs between water delivery and carryover storage, environmental flows and socioeconomic uses, etc. It was decided for this assessment that the manner in which water is routed through the system should resemble present day allocation philosophies. In CALSIM II, a majority of those tradeoffs are supported by codified state and federal allocation priorities, which have significantly evolved since 1992 (Brickson, 1998). The Baseline model was available in several versions, representing different subsets of state and federal regulations (CDWR, 2001). The version used in this study features implementation of the Delta Water Quality Control Plan codified in California State Water Rights Decision 1641 and is subsequently referenced as a D1641 study using the Baseline model.

Input Data Development for the Operations Model

Climate change would potentially affect several types of model input data: reservoir inflow time series, hydrologic "year-type" classifications that determine constraints on system operations, valley floor interactions between ground water and surface water, water consumption among urban and agricultural users, water allocation contracts, and reservoir operations regulations, etc. For these analyses, only *reservoir inflows* and *hydrologic year types* were adjusted for each projection period case.

Development of reservoir inflow time series for each projection-period case was performed using the hydrologic response ratios shown on Figure 3. For example, the October monthly ratio shown for the Sacramento River basin under the HadCM2025 case (Figure 3) was used to adjust all "present climate" October inflows at Lake Shasta from 1922 to 1994 to create corresponding "HadCM2025" October inflows. This step was repeated for November, and so forth. The operations model has 18 reservoir inflow time series that account for runoff from the Sierra Nevada and Cascade Mountains. Therefore monthly ratio patterns for the five basins developed by Miller *et al.* (2003) had to be blended as necessary to produce a monthly ratio pattern for each reservoir inflow node in the model. For example, ratio patterns for the North Fork of the American River and the Merced River were used to develop a ratio pattern for the Stanislaus River, which was then used to generate "climate change" inflow data into New Melones Reservoir. Blending was always a weighted combination of two sets of monthly ratio patterns using a weighting scheme of either 25 percent and 75 percent, or 50 percent and 50 percent.

Development of hydrologic year types under each projection period case was based on the relationship between Baseline reservoir inflows and Baseline year type designations. A year type designation describes hydrologic conditions in an October through September water year and can be classified at any time during the water year after January. The designation is referenced to a classification system and is based on estimates of current water supplies and forecasts of runoff throughout the remainder of the year. The Baseline model uses seven different classification systems to determine operations in different subareas of the Central Valley given D1641 allocation priorities. To develop projection period year types under each classification system, the inflow thresholds associated with Baseline year types were kept constant and the inflow data from each projection period case were applied against these thresholds to obtain projection-period year types.

Assessment Limitations

A key limitation of this assessment is that it represents only a small portion of the climate change possibilities described in IPCC (2001). To compare, this assessment is based on one CO_2 increase scenario whereas the IPCC (2001) report describes numerous other emissions possibilities and standardized rates of CO_2 increase. This assessment considers projections of the one CO_2 increase scenario using two global climate models (HadCM2 and PCM), whereas the IPCC (2001) report references 19 atmosphere ocean general circulation models that were used to develop projections under the given scenario (i.e., Table 9.1 in IPCC, 2001). Uncertainties are compounded further when dynamical versus statistical downscaling techniques are considered for translating global projection results into basin scale effects: this assessment used a statistical method (see the Hydrologic Response Development Section). Therefore, this study only represents a limited set of the potential projections of precipitation, temperature, and runoff in the San Joaquin River region in response to potential climate change.

This study does not account for the potential coupling of Central Valley land cover change and regional climate change in response to CO_2 increases. It might be possible to account for this coupling if atmosphere-ocean general circulation models included land cover parameterizations that are coupled to atmospheric state variables. This would allow for simulation of land cover responses to climate change and the dynamic feedback of land cover shifts on atmospheric conditions. Accounting for this coupling and its effects has been gaining increasing attention in climate projection research (Chase *et al.,* 2001; Pielke, 2002).

Potential sea level rise was not considered in this assessment. Changes in sea level would affect the distribution of salinity concentrations in the San Francisco Bay-Estuary and cause further salinity intrusion into the Delta. Increases in Delta salinity at CVP and SWP export pumping facilities would adversely affect water quality and water supply reliability. If Delta outflows decrease with climate change, then salinity intrusion would increase and sea level rise would exacerbate this effect. Conversely, if Delta outflows increase, then salinity repulsion would ensue, but sea level rise would counter the effect. Assessing the balance between climate change impacts on Delta salinity conditions through changes in outflow and sea level could be studied through hydrodynamic modeling of the Delta, which was outside the scope of this assessment.

Finally, changes in flood event potential were not evaluated in this assessment. Such changes could have significant impact on wet season flood control protocols in reservoir operations. Hydrologic responses to climate change are represented herein as functions of monthly mean changes in precipitation and temperature over 30-year future periods (Miller *et al.,* 2001). Changes in variability are embedded in the monthly mean changes. It is quite possible that climate variability will be different with any form of climate change. However, to assess the potential impacts on flood potential, it would be necessary to quantify changes in climate variability using climate projection statistics at time scales that are compatible with flood event durations (e.g., one to several days). Projections on these time scales were not considered in this assessment and have not been discussed quantitatively in the most recent consensus reports on global climate change (USGCRP, 2001, unpublished report; IPCC, 2001).

RESULTS

Climate change impacts on the water resources of the San Joaquin River region are summarized separately in relation to HadCM2 and PCM climate projections in sections to follow. Reservoir inflow impacts for each projection period case are measured by changes in monthly mean inflows over the 73 years of simulation. Impacts on storage, reservoir releases, and water deliveries are measured by changes in monthly mean decision patterns during three groups of simulation years: *DRY, NORMAL*, and *WET*. Definition of these groups was based on ranking the simulation years by total annual reservoir inflow within the Sacramento and San Joaquin River regions. This ranking of 73 inflow years was then broken into three groups: the 27 lowest inflow years were labeled as *DRY*, the 27 highest inflow years were labeled as *WET*, and the middle 29 years were labeled as *NORMAL*. Finally, impacts on the ability of SWP and CVP operators to meet Delta water quality management objectives while maintaining other operating objectives in the San Joaquin River region were measured using changes in a metric of salinity intrusion into the Delta.

HadCM2-based Climate Change Impacts

Reservoir Inflow. Under the HadCM2 projection, surface water inflows within the greater Central Valley would increase dramatically. The HadCM2025 results show that the combined amount of inflow from the Sacramento and San Joaquin River regions during the winter/spring period (i.e., December to May) would increase 51 percent relative to Baseline conditions. Much of this increase is concentrated in the months of December through March (Figure 4). Annual mean inflow would increase 39 percent (Figure 5). In HadCM2065, the increases in winter-spring and annual inflow would become 74 percent and 53 percent, respectively.

Focusing on just the San Joaquin River region of the Central Valley, projected inflow increases are even more dramatic. Results from the HadCM2025 projection show that winter-spring inflows would increase 80 percent relative to Baseline inflows. The average annual inflow would increase 57 percent. In HadCM2065, these percentages rise to 127 percent and 85 percent for winter/spring and annual periods, respectively.

Operating Decisions Regarding Stored Water, Releases, and Deliveries. Due to the constraint of Baseline storage capacities, the east side surface water reservoirs would only be able to retain limited amounts of the HadCM2 projected increases in inflow to assist supply conservation. In the HadCM2025 case, the greatest opportunity for retaining inflow increases occurs during *DRY* years (e.g., New Melones Reservoir, Figure 5), with increases becoming more

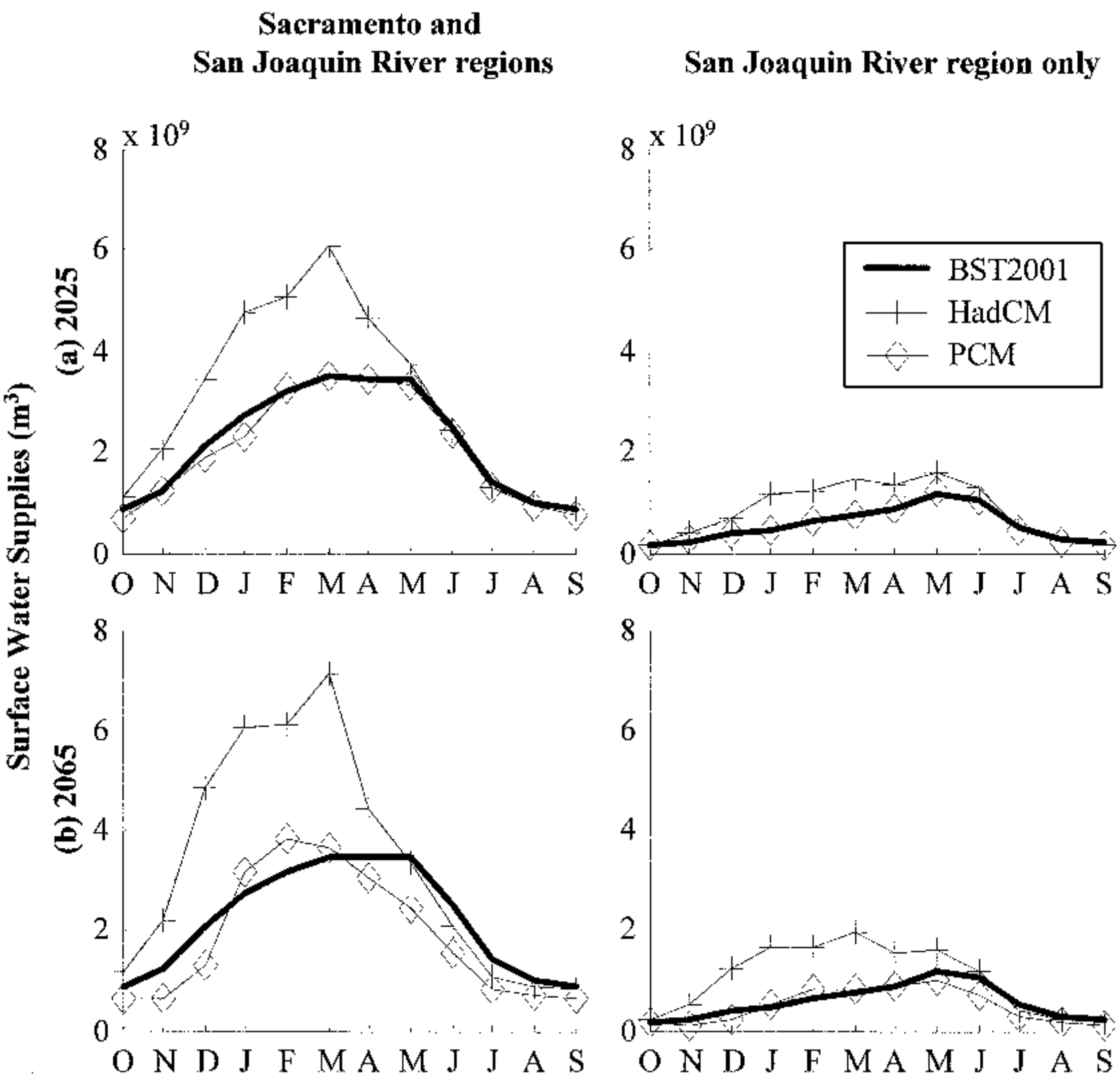

Figure 4. Simulated Surface Water Supplies for the Combined Sacramento and San Joaquin River Regions, and for the San Joaquin River region only: (a) 2025 and (b) 2065.

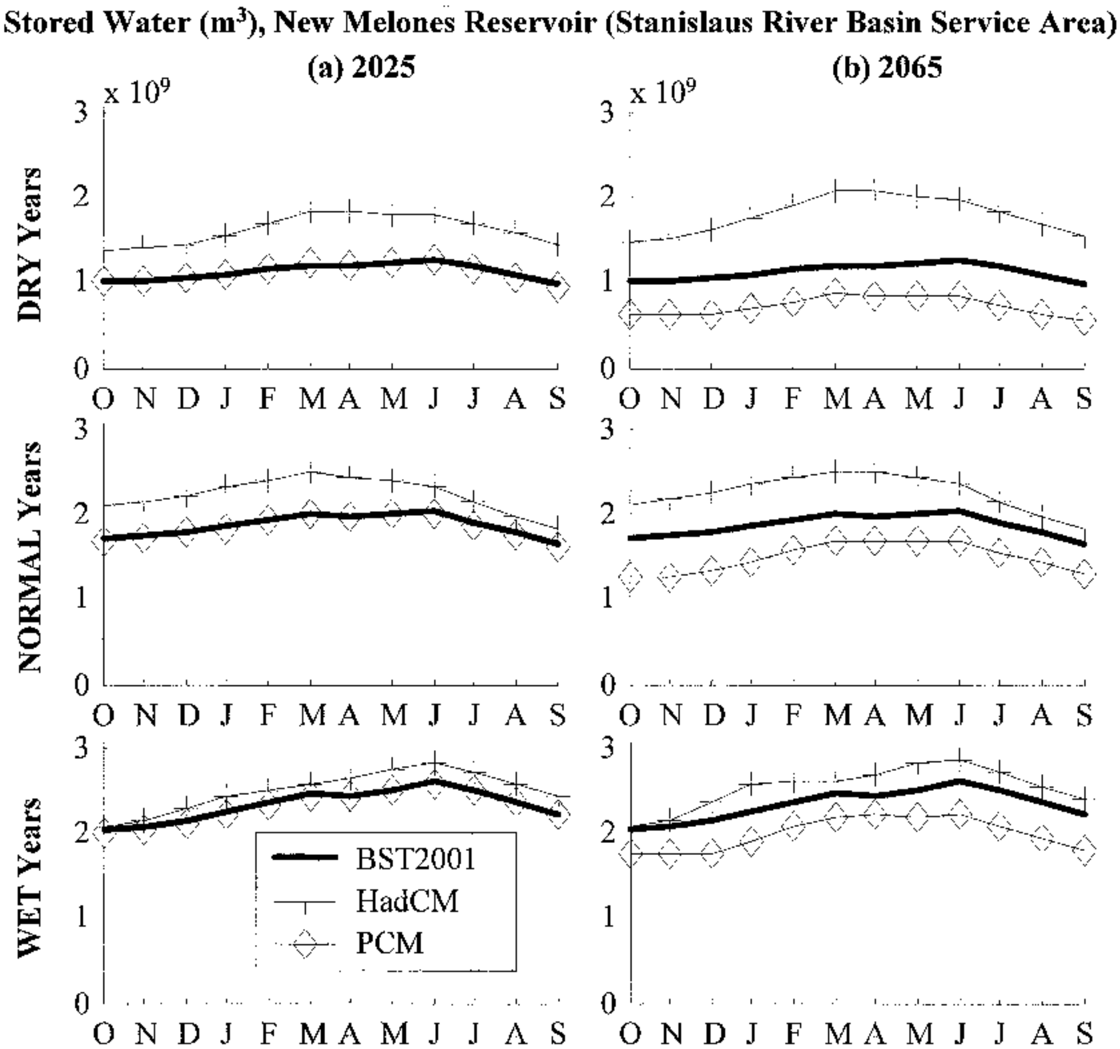

Figure 5. Simulated Monthly Mean Storage in New Melones Reservoir for Relative *DRY, NORMAL*, and *WET* Years: (a) 2025 and (b) 2065.

pronounced by 2065. In those same *DRY* years, simulated release volumes experience minor changes in the HadCM2025 case (e.g., New Melones Reservoir, Figure 6). This is because Baseline storage, releases, and east side water deliveries are somewhat balanced with east side deliveries being very close to Baseline demand levels (results not shown). Therefore, when the Baseline demands are held constant while the system is subjected to HadCM2025 inflow conditions, there is an opportunity to increase HadCM2025 stored water volumes during *DRY* years because there is little residual demand to be satisfied that could not be satisfied under Baseline conditions (Figure 7).

For *WET* years, storage volumes experienced little change and release volumes increase significantly. This is especially the case during winter months because residual storage capacity during winter is small during the Baseline *WET* years. Thus, as inflow increases dramatically during the HadCM2025 and HadCM2065 *WET* years (Figure 4), release volumes are forced to increase in kind (Figure 6).

Whereas limited impact was found for the San Joaquin River region's east side deliveries (Figure 7), significant delivery improvements were observed for the region's west side under HadCM2 climate change. This is apparent when looking at simulated delivery volumes relative to demands (i.e., delivery levels). Delivery levels were evaluated in aggregate for CVP agricultural contractors located south of the Delta (Figure 8). These contractors rely on deliveries from North-of-Delta supplies and the ability of the CVP operators to convey those supplies through the Delta export facilities under assumed export restrictions (e.g., those codified in D1641). Under Baseline conditions, the average annual delivery levels were 33 percent, 74 percent, and 92 percent for *DRY, NORMAL*,

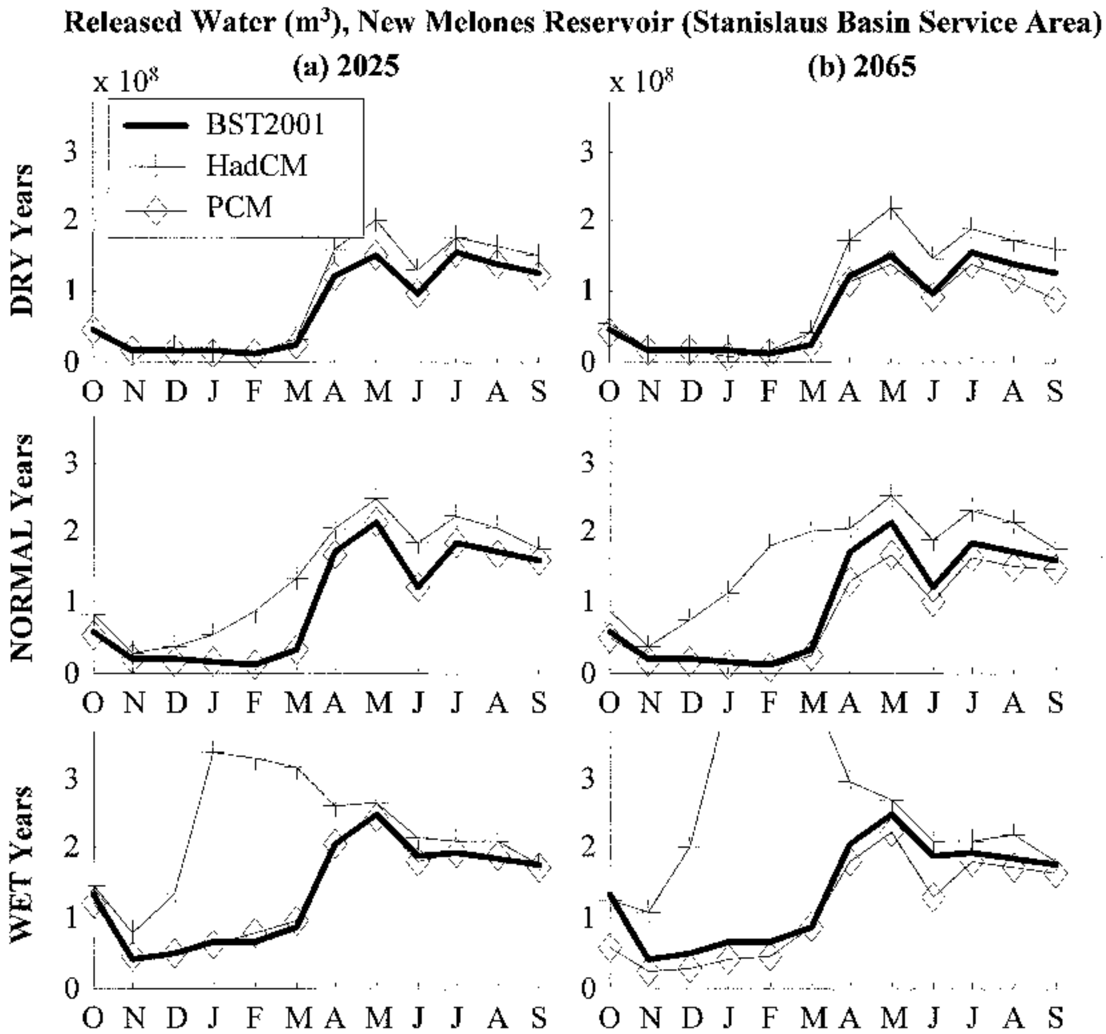

Figure 6. Simulated Monthly Mean Release From New Melones Reservoir for Relative *DRY, NORMAL*, and *WET* Years: (a) 2025 and (b) 2065.

and *WET* years, respectively. Sub-100 percent levels occur when North-of-Delta supplies are insufficient and/or Delta export capacity is too restrictive to support delivery of full South-of-Delta demands. Under HadCM2025 conditions, there are substantial increases in Sacramento River region inflows causing relief on delivery level restrictions related to North-of-Delta supplies. Thus, it was not surprising that delivery levels to CVP South-of-Delta agricultural users improved to 62 percent, 87 percent, and 98 percent for *DRY, NORMAL*, and *WET* years, respectively. By 2065, they are at 63 percent, 89 percent, and nearly 100 percent. So it would seem that given the conditions of Year 2001 land use and D1641 allocation priorities, there would be a great opportunity for west side San Joaquin River Basin agriculture to benefit under the HadCM2 climate projection.

It is interesting to note that HadCM2 impacts on reservoir operations and deliveries produce results that are strikingly different than impacts assessed in previous studies (e.g., Gleick, 1987; Dracup and Pelmulder, 1993, unpublished report). Earlier studies were based on an assumption of no precipitation change, which led to findings that global warming would result in warmer winter storms, less snowpack accumulation, less spring/summer streamflow and water supply, and more frequent water shortages during summer and autumn months (i.e., the dry season). The HadCM2025 results support the notion of warmer winter storms and less snowpack accumulation relative to rainfall/runoff during winter. However, the HadCM2025 results do not support the notion of reduced water supply and increased water shortages during the dry season. In fact, the results suggest that dry season deliveries would increase

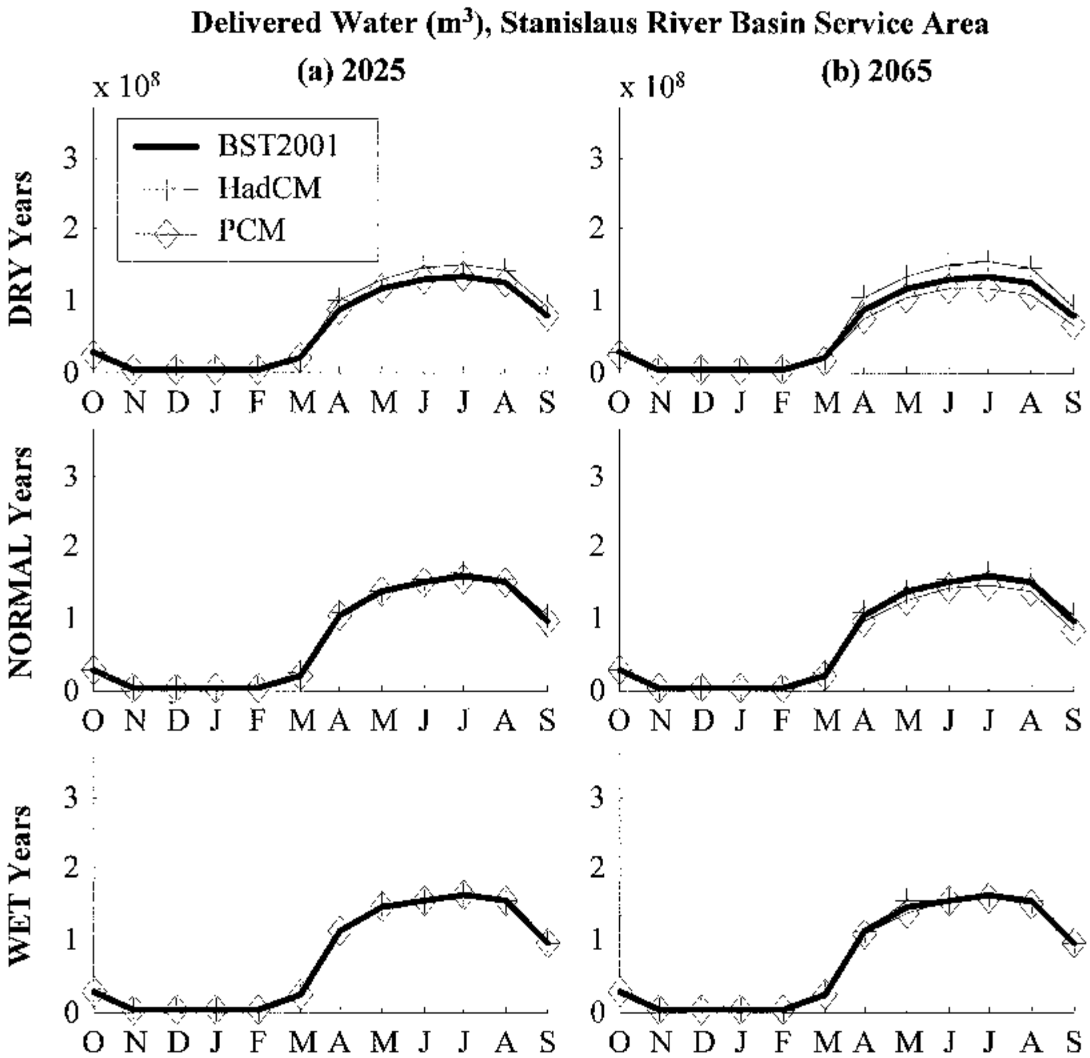

Figure 7. Simulated Monthly Mean Delivery in an East side Service Area Within the San Joaquin River Region for *DRY, NORMAL*, and *WET* Years: (a) 2025 and (b) 2065.

(Figures 7 and 8), largely due to the considerable increase in average/annual precipitation under the HadCM2 projection.

Ability to Manage Water Quality in the Delta. The CVP and SWP jointly control reservoir releases throughout their systems to manage water quality throughout the Central Valley. Success in managing valley wide water quality is inferred by salinity and flow indicators situated in the Delta, many of which are codified in D1641. Of these indicators, the simulated X2 metric was used for measuring how climate change would impact the abilities of CVP and SWP system operators to manage Delta water quality. The X2 metric describes seawater intrusion into the Delta. It represents the location of a 0.2 percent constant salinity boundary in the Delta region measured upstream from the Golden Gate Bridge. Water quality objectives in D1641 set requirements for the location of X2, which is partly managed by reservoir releases from the CVP and SWP systems.

Delta water quality impacts from upstream operations are potentially most severe during low-flow conditions. Consequently, changes in X2 locations between the Baseline simulation and those of the projection period cases were measured during a critical drought sequence common to all simulations: simulation years 1987 to 1992. This drought sequence reflects an actual meteorological drought that was experienced in California during those historical years.

Focusing on the dry season months of the drought sequence (i.e., April to September of each water year that spans October to September), simulation results

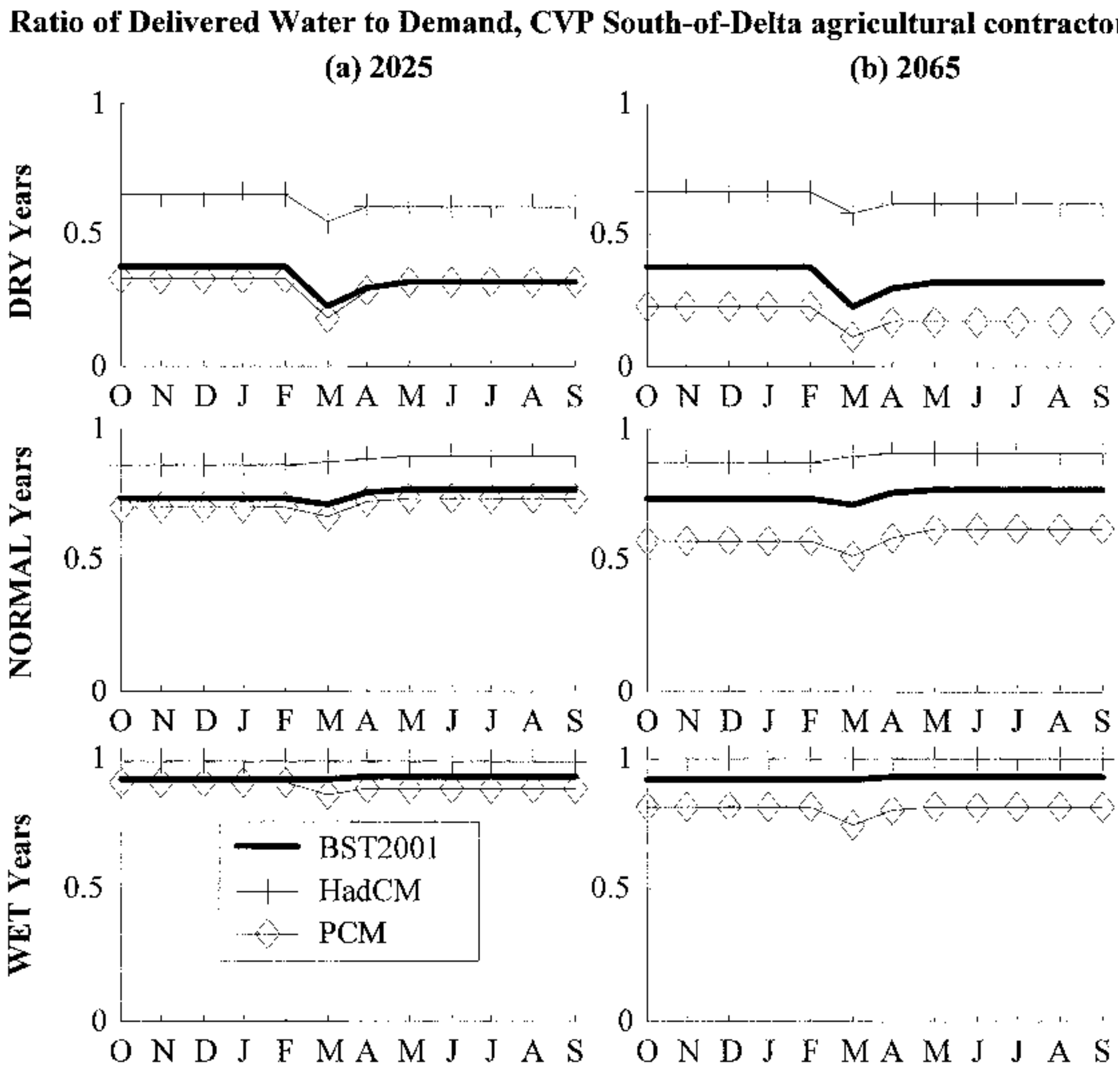

Figure 8. Simulated Monthly Mean Delivery Levels (i.e., ratio of delivery to demand) for All CVP Agricultural Users South of the Delta, Representing the West side Service Areas of the San Joaquin River Region, for *DRY, NORMAL*, and *WET* Years: (a) 2025 and (b) 2065.

show minimal changes in X2 locations in the HadCM2025 or HadCM2065 cases relative to the Baseline case (Figure 9). X2 reductions would be expected given the large increases in Central Valley annual inflows and stored water supplies during *DRY* years (Figure 5). Noticeable reductions are evident in simulation year 1989, but not in the other years. So it appears that the model had enough water routing discretion under D1641 allocation assumptions to not release more water during dry season months of this drought sequence to reduce X2 locations. More frequent reductions to X2 occurred during winter months as substantial increases in Delta inflows are enough to cause flushing of Delta salinity.

PCM Based Climate Change Impacts

In switching the discussion from HadCM2 related impacts to PCM related impacts, recall that the PCM projection involves precipitation decreases over California while the HadCM2 projection involves precipitation increases. To foreshadow the findings of this section, PCM based results are more consistent with the conclusions of earlier studies on California climate change impacts (e.g., Lettenmaier and Gan, 1990; USBR, 1991; Miller *et al.,* 1999): global warming will result in warmer winter storms, less snowpack accumulation, and reduced spring/summer water supplies.

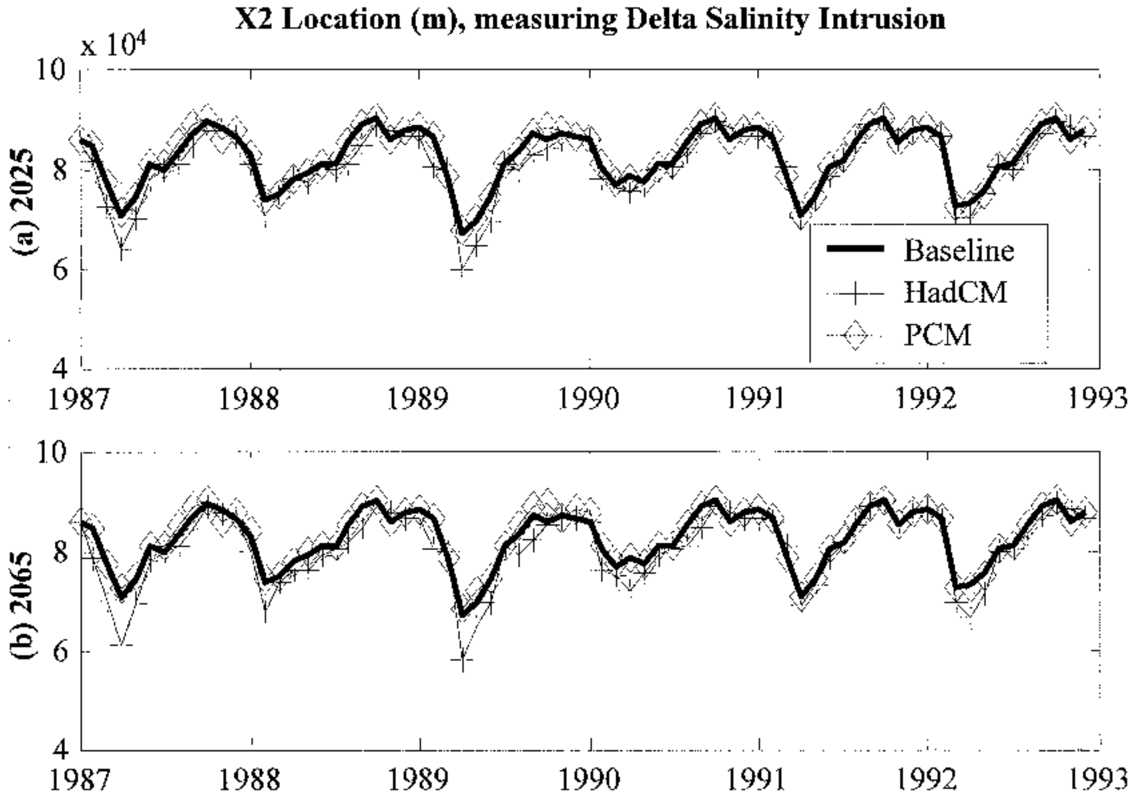

Figure 9. Simulated X2 Location Within the Delta (i.e., the 0.2 parts per thousand isohaline), Measured Upstream Relative to the Golden Gate Bridge, Assessed During a Multi-Year Meteorological Drought Sequence From the Operations Simulation (i.e. simulation years (1987 to 1992)): (a) 2025 and (b) 2065.

Reservoir Inflow. PCM2025 results show that April through September, or spring/summer, inflow volumes for the combined Sacramento and San Joaquin River regions (Figure 4) would decrease 5 percent relative to Baseline conditions. Annual inflows are projected to decrease 5 percent. By PCM2065, these decreases would become more significant as spring/summer and annual inflows are 28 percent and 14 percent less than Baseline inflows, respectively.

Focusing on just the inflows in the San Joaquin River region, the impacts are found to be slightly different from those for the greater Central Valley (Figure 5). For example, while PCM2025 annual inflows for the combined Sacramento and San Joaquin River regions would decrease by about 5 percent, there would be virtually no change in inflows for just the San Joaquin River region. Similar comparisons are made for the spring/summer inflow period. By PCM2065, the spring/summer and annual inflows are 23 percent and 13 percent less than Baseline inflows, respectively.

Operating Decisions Regarding Stored Water, Releases, and Deliveries. Decreases in inflows to the combined Sacramento and San Joaquin River regions under PCM climate change would lead to reduced water supplies and increased demand competition throughout the Central Valley. This impact is subtle by 2025 and more apparent by 2065 (Figures 5 through 8). Focusing on storage and release decisions, the results for the Stanislaus River basin are used to represent PCM related impacts on the San Joaquin River region's east side. Stored water and release impacts would remain largely unchanged through PCM2025 because reservoir inflow is largely unchanged. However by 2065, the reservoir inflow decreases significantly and causes storage and release decreases during all simulation year types (Figures 5 and 6).

East side delivery impacts are found to be slight compared to impacts on storage and release volumes (Figure 7). This finding relates to the assumed carryover storage rules for east side reservoirs in the Baseline model. Carryover rules set the desired amount of water to that which must be retained in the reservoir at the end of the water year for use in the following water year. If more conservative carryover rules are imposed, then east side deliveries would be more adversely impacted under PCM climate change.

West side deliveries impacts are more visible in the simulation results than their east side counterparts (Figure 8 versus Figure 7). Delivery level impacts to "CVP South-of-Delta agricultural contractors" are again used here to represent west side deliveries impacts, similar to their use in the HadCM2 results assessment. Reduced Sacramento River region inflows and increased constraints on Delta export activities due to reduced Delta inflows cause "delivery level" reductions to these contractors. The simulated delivery levels for this user group in the Baseline case were 33 percent, 74 percent, and 92 percent for *DRY*, *NORMAL*, and *WET* years, respectively. In the PCM2025 case, these deficiencies worsen to 30 percent, 71 percent, and 89 percent. By 2065, they are at 19 percent, 58 percent, and 80 percent. The severity of these reductions is related to D1641 allocation assumptions, where meeting South-of-Delta water demands is placed at a lower priority relative to meeting Delta water quality and ecosystem management objectives. If those protocols were relaxed in response to more frequent and severe water shortages, then the west side delivery level decreases would be somewhat mitigated.

Ability to Manage Water Quality in the Delta. As in the assessment of HadCM2 impacts on Delta water quality, the PCM related impacts on Delta water quality are measured by changes in X2 locations describing Delta seawater intrusion. Reductions in Central Valley inflows and stored water supplies would conceptually reduce water available for augmenting Delta outflow and lead to further seawater intrusion into the Delta region. However, simulation results show that the CVP and SWP systems can be operated with enough flexibility under D1641 allocation protocols to balance allocation cuts to agricultural and urban deliveries in a way that allows Delta water quality objectives to be maintained under PCM climate change (Figure 9). Results for both PCM2025 and PCM2065 show that there are virtually no changes in the X2 position relative to BASELINE conditions during any simulation months from this drought period sequence.

DISCUSSION

Planners from the California Department of Water Resources (CDWR) are considering climate change in their update of the California State Water Plan (K.D. Nelson, February 27, 2002, personal communication). Planners from the state/federal CALFED program are also considering climate change in their development of projects for enhancing water supply reliability, ecosystem resources, and channel levee stability in the Delta. The consideration of climate change in both planning initiatives stems from the reality that any proposed infrastructure project would be expected to serve the region for at least the next half-century. Any financial investment in infrastructure would be poorly spent if it does not accommodate for altered hydrology under climate change. Moreover, there is the risk that such infrastructure would fail to protect the public against the hazards of more severe flood events or water supply shortages under climate change.

This paper presents an assessment on impacts uncertainty for the water resources of the San Joaquin River region. The findings of this assessment are relevant to both the DWR and CALFED planning initiatives. However, the impacts from this assessment represent only a limited set of potential climate change scenarios (i.e., one CO_2 increase scenario and two global climate projections of that scenario evaluated at two future periods). Moreover, that limited subset was still diverse enough to infer a vast range of potential climate change impacts for the water resources of the San Joaquin River region and the greater Central Valley.

The task of applying this information to guide current regional planning efforts is confounded by the breadth of the assessed impacts and how that breadth is interpreted. Since the HadCM2 and PCM projections of the CO_2 increase scenario are presented as being equiprobable (IPCC 2001), the impacts associated with each projection must also be viewed as equiprobable. For planners, the information from the Results section is difficult to utilize because it goes in two drastically different directions. The HadCM2 projections suggest prioritizing investment in CVP/SWP capabilities to manage wet season flood potential, either through increased storage or channel capacities, compared to investment in water supply development. The PCM projections suggest that projects should be developed to mitigate future water supply shortages and pay relatively less attention on flood control enhancements. The question of which planning direction is more advisable cannot be answered without making a statement on which projection case is more probable (HadCM2 or PCM). So, given the incoherency of impacts presented in this assessment, it is of interest to consider what might be done in the present time in terms of two distinctly different actions: mitigation project selection and contingency planning.

On the issue of selecting mitigation projects, it seems that implementation schedules for capital improvements for the systems in the Central Valley are revisited every five years. Thus, there seems to be an opportunity to reconsider climate change mitigation issues and project selection rather frequently compared to the pace of climate change inferred by either the HadCM2025 or PCM projections. Thus, it seems advisable to delay selection of mitigation projects until future planning cycles. Project selection might commence when expected regional precipitation projections over California become more precise or the span of uncertainty becomes largely the same "sign" in terms of precipitation changes relative to present climate.

On the issue of contingency planning, resource managers from the San Joaquin and Central Valley regions can initiate proactive measures. A main action would be to apply their planning models like CALSIM II in comprehensive and strategic studies that involve expanded sets of planning scenarios, conditioned on different climate change, land use, and allocation policy assumptions. Such efforts would probably expand the assessed range of impacts already described in the Results. This would exacerbate the problem of the impacts breadth being too incoherent for guiding the selection of mitigation projects. However, the expanded range would represent a more comprehensive set of climate change, land use, and policy scenarios. Moreover, it may be possible to develop nonuniform probability distributions of the expected impacts, unlike the "two projection" assessment presented herein. Nonuniform probability distributions might enable the application of risk management techniques for supporting the selection of projections or operational strategies to mitigate climate change impacts.

To support contingency planning, agency access to information on various CO_2 increase and climate projection possibilities will have to be improved. The need for this improvement stems from the fact that for mitigation projects to be selected and implemented, agencies will to have to conduct or oversee their own comprehensive impacts assessments. In those studies, agencies will have to take responsibility for characterizing and defending their interpretation of impacts uncertainties. This task becomes more defendable if the assertions are based on a suite of CO_2 increase scenarios and model projection of those scenarios, even if each individual climate projection is viewed as equiprobable because the collection of impacts scenarios might indicate "central tendencies" of impacts.

To improve agency access to climate projection information, coalitions need to be built between agencies and climate modeling groups. Both parties need to negotiate "nature of information" protocols representing information that is suitable to guide contingency planning and that can be feasibly developed by the climate modelers (e.g. projection information similar to that described in the Hydrologic Response Development Section, but downscaled to all "watershed" units of appropriate planning scale throughout the Central Valley). Once information protocols are established, a web resource might be developed to collect this information from any climate modeling group and distribute it to agencies. An agency would assume responsibility for hosting the web data center. Climate modeling groups would be invited to submit their global projections of various CO_2 increase scenarios per negotiated information protocols. Submitted projection information would presumably be referenced to information described in IPCC reports. Planners could then select and utilize this information in their planning efforts. The responsibility of how the information is applied during impacts assessment would rest on the planners. Presuming that the web-resource would eventually store a multitude of scenarios and projections per scenario, planners would then have access to the breadth of information required to do comprehensive contingency planning described above.

CONCLUSIONS

This assessment characterizes uncertainties of various climate change impacts on the water resources of the San Joaquin River region in California. These impacts are based on climate change forced by a 1 percent per year CO_2 increase scenario projected using two global climate models (HadCM2 and PCM). The two models produce significantly different precipitation projections over California in response to the common CO_2 increase assumption. These precipitation projections are reasonable choices for bracketing the uncertainty of California hydroclimatic response to global warming.

Impacts were assessed in terms of changes to reservoir inflows, storage volumes, release volumes, and water deliveries to the San Joaquin River region. Impacts were also evaluated for changes in water quality in the Delta region and hydrology in the greater Central Valley. Based on the HadCM2 projections, there would be increased reservoir inflows, increased storage limited by existing capacity, and increased river flows, increased west side deliveries, and little impact to Delta water quality. The PCM projection leads to similar minimal impacts to Delta water quality. However, the other PCM impacts would be decreased reservoir inflows, decreased storage, decreased river flows, and severe reductions in west side deliveries. The finding of minimal impact on Delta water quality conditions relative to reductions in west side delivery levels is predicated on the D1641 allocation priorities assumed for the simulations.

The primary findings of this study are that the impacts suggested by the HadCM2 and PCM projections are divergent and equiprobable. The range of possibilities suggested by these impacts is too vast to support selection of mitigation projects in current planning cycles. Since there is opportunity to revisit infrastructure development plans approximately every five years, it seems prudent to delay project selection until impacts uncertainties are reduced. This reduction is tied to reducing uncertainties in the precipitation projections over California. In the meantime, San Joaquin River region and Central Valley water resources planners can proactively focus their efforts on preparing mitigation strategies. This action of contingency planning will require application of their planning tools (e.g., CALSIM II) and consideration of a variety of CO_2 increase scenarios, climate model projections, land use projections, and allocation policy assumptions. The regional agencies currently lack access to CO_2 increase scenarios and global climate projections. They can overcome this obstacle through coalition building with climate modeling groups and by developing and managing data information systems intended for collecting and distributing climate projection information. In this process, planning agencies would gain the opportunity for controlling the usage and interpretation of climate projection information in their planning processes.

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